THE IMPACT OF MULTI-LEVEL PATH PLANNING ON UNMANNED GROUND VEHICLE TACTICAL BEHAVIOR

Marshal A. Childers*, Barry A. Bodt, Ph.D., Susan G. Hill, Ph.D.
U.S. Army Research Laboratory
Aberdeen Proving Ground, MD 21005

Richard Camden
L3/MPRI
Aberdeen Proving Ground, MD 21005

ABSTRACT

In February 2008, the Robotics Program Office of the U.S. Army Research Laboratory and General Dynamics Robotics Systems (GDRS) conducted an assessment of path planning technologies designed to improve Unmanned Ground Vehicle (UGV) autonomous mobility. The purposes of this study were to determine the impact when perceptive and deliberative planners are integrated to enable a UGV to maneuver through terrain, and to further develop a methodology for assessing autonomous UGV tactical behavior. The assessment was conducted at Fort Indiantown Gap, PA over vegetated terrain using the eXperimental Unmanned Vehicle (XUV). The terrain and areas of operation over which the assessment was conducted required the UGV to select its course based on available a priori terrain data, new sensed information in the local environment, and required mission attributes. In this paper, we will share qualitative assessment data on performance of the technologies and recommendations for improving future technology assessments.

1. INTRODUCTION

In FY 2003, the ARL Robotics Program Office and GDRS conducted, with testing oversight by the National Institute of Standards and Technology, an extensive three-site experiment of an autonomous navigation system (ANS) (Camden et al., 2005). The ANS relied on perceptive level planning to achieve a manually pre-determined route of way points in rolling desert, rolling vegetated and urban terrain. The ANS was given a Technology Readiness Level 6 designation by Future Combat Systems in part due to this study. Interim advances in the Operator Control Unit (OCU) greatly simplified manual route planning, while perception algorithms and hardware continued to mature. More recent developments in the architecture allow for deliberative planning in a move toward tactically intelligent behaviors (Childers et al., 2007).

In order for unmanned ground vehicles to be effective for the Soldier, they must be capable of maneuvering through relevant terrain in a tactical manner that supports mission tasks. The described assessment is part of ongoing basic and applied research conducted under the ARL Robotics Collaborative Technology Alliance (CTA) that develops enabling technology for UGV tactical behaviors.

The motivation for the recent work is to enable the XUV to use the best information available from multiple sources and to bridge the deliberative and perceptive level planning such that the unmanned ground vehicle has the ability to use information on terrain features at multiple ranges to tactical advantage. Deliberative (i.e. higher level) planning draws on the objective of the operation and the global map of *a priori* information (elevation and feature data). Deliberative planning consists of separate layers to independently assess costs for traversing terrain; the current configuration considers costs associated with mobility, time, and exposure to a known threat. Those layers are combined using a weighted heuristic into a single planning layer for use by the route planning algorithm. Different weight combinations map into various tactical concepts, which allow the OCU to provide explicit choices to the user such as “prefer roads” or “stealth”; weights can be individually set based on the mission goals. The long-term goal is to develop technology that enables the use of the best information available from multiple sources and fused at the deliberative level. On the time horizon for UGV autonomous maneuver, the deliberative layer provides long-range information at a course resolution that consists of both a priori (pre-mission) data and information that is received from external sources. At this level, the vehicle position is considered with respect to the world (absolute coordinates).

The resolution and accuracy of a priori data used to generate route paths are often insufficient to enable a UGV to navigate without requiring it to negotiate scenarios, such as cul-de-sacs, from which the vehicle could not autonomously extricate itself. The perceptive layer provides close-range information at a finer resolution that is provided by the onboard vehicle sensors. The current

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autonomous mobility sensors of the XUV permit planning at the perceptive level out to approximately 60 meters depending on the environmental conditions. Ongoing technology development, under the direction of the ARL Robotics CTA, is critical in providing a mid-range (~500m) sensing capability to provide information at a range and resolution that bridges the gap between the current sensor range and the global level (beyond 1 km).

Deliberative and perceptive level planning are integrated through the field cost interface (FCI) and best information planning (BIP). Local perception provides costs at ~5 Hz rate for local paths finishing along the arc formed by the sensor range. FCI is a feature that provides a bridge between deliberative layer planning and local planning by assigning costs at ~1 Hz rate along the perimeter of the sensor range representing the entry points for continued routes to the objective way point. FCI does not receive a set of long-range route points to follow but rather receives a so-called “cost field”, which is a set of costs to get from any point on a 60m-radius circle centered at the vehicle to the next waypoint (specified by the operator). FCI permits navigation to virtually any point on this circle. For the present technology assessment, BIP is confined to the use of sensed data flowing up from the perceptive level. It updates the deliberative planning map and replanning at the deliberative level based on the updated map. Using this updated information may be especially useful with imperfect *a priori* knowledge of the terrain. It is this bi-directional flow of information that is the focus of the assessment.

In order to tie the different planners together, the XUV has an onboard Autonomous Command and Control (ACC) component. The ACC allows the XUV to remain aware of the mission and global environment by providing an interface between the world model of a priori elevation and terrain feature data, the perception level of autonomous mobility, the low-level XUV control, and the status of the XUV.

2. DATA COLLECTION

In order to assess the impact and interplay of the perceptive and deliberative planning layers on the ability of the XUV to maneuver through relevant terrain, two evaluations were conducted at Ft. Indiantown Gap in training areas B9C and B12. The approach was to leverage environments where a combination of run conditions could be exercised and the resultant behavior from the XUV observed.

This assessment of information planning technologies consisted of one XUV, one operator using an OCU, a safety chase vehicle with a driver and a safety officer (with an E-stop radio), and a data recorder for noting observations for each run. All runs consisted of a starting waypoint and an ending waypoint with no intermediate waypoints provided. In the cases where a priori elevation and feature data were used in the generation of an initial route plan, the planner generated route points to be achieved along that route. Feature data used in the assessment consisted of tree lines, roads, and “no-go” areas that contained attributes which could harm the XUV (e.g. water hazards, stumps). In the event that the XUV could not plan a route around an obstacle or out of a cul-de-sac, the XUV autonomously backed up to gain a better perspective of the environment and subsequently attempted to use perceptive level planning to find a suitable path. This programmed behavior was attempted up to three times with the distance of the backup increasing with each attempt (5, 10, and 15 meters). If after the third backup the XUV was still unable to plan a route beyond the obstacle, the condition was referred to as “maximum backups” whereupon the operator was notified to intervene. Options for operator intervention depended upon run configuration. In runs that were based on perceptive level planning, the operator was required to teleoperate the vehicle past the most immediate obstacle and then re-execute the original route plan from that location. For runs that included deliberative level planning, the operator initiated a) a 15 meter backup and b) the generation of a new route plan based on data sensed from the local area and a priori elevation and feature data.

The portion of Area B9C used in this assessment consists of a relatively flat, open area of approximately three acres that contains numerous shipping containers arranged in such a way as to simulate a small Military Operations on Urbanized Terrain (MOUT) site. Figure 1 is a sketch of

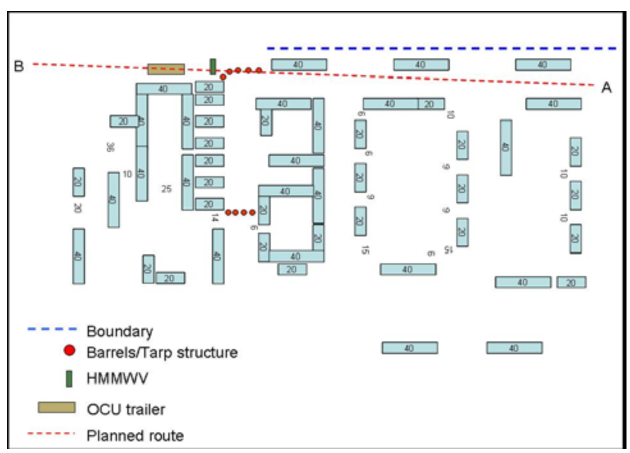

Fig. 1. Assessment configuration for Area B9C

the MOUT site which is constructed from steel dry-freight shipping containers of two lengths, twenty meters and forty meters, and with a cross section that is approximately eight feet by eight feet.

The start and end points for each run are depicted as A and B, respectively, and the initial path for all runs was the dashed straight line path shown in orange. No a priori feature data was used for this portion of the assessment and therefore, the MOUT site features were not used during the generation of route plans. In order to bound the problem, a boundary line, shown in the figure as a blue dashed line, was entered into the a priori data to prevent the XUV from planning a route that circumvented the MOUT site. Although for this scenario it would appear that the better route to the goal is to avoid the containers altogether, this option was removed so that we might assess the ability of multi-level mobility planning technologies to enable the XUV to plan a way out of a cul-de-sac. Additional man-made obstacles in the form of construction barrels, and tarps were added to create mobility obstructions. The available paths within the MOUT site were narrow with respect to the XUV turning radius. This area did afford multiple alternative routes to the XUV in order to achieve the end point.

The mobility planning technologies were also assessed in a portion of training area B12. Figure 2 shows the area of operations which contains open fields, tree lines, and unimproved trails.

Fig. 2. Assessment configuration for Area B12

This area provided another opportunity to create a cul-de-sac in a more open environment in comparison to that of area B9C. A combination of tarps, construction barrels, and HMMWVs were used to block the initial planned path of the XUV. The width of the cul-de-sac was approximately fifty meters which provided plenty of room for the XUV to maneuver. The planned route was the straight line path shown in orange and was approximately four hundred meters in length. The alternative route, shown in green, was a traversable route to the goal over an unimproved trail that was part of the a priori data.

The assessment conducted in each of the described areas was based on a schedule of runs which varied the available conditions. Primarily, the available parameters for run conditions included slight variations of the start and end locations, inclusion/exclusion of available a priori elevation and feature data, and the inclusion/exclusion of the BIP and FCI path planning technologies.

The conditions for each run were established by an engineer prior to the start of the run. A laptop computer was used to run configuration script files and transmit the appropriate configuration commands to the XUV via a wireless local area network link. Each run began with the XUV located at the selected start point and oriented towards the end point. The operator used the OCU to generate a route plan using one waypoint for the start location, one waypoint for the end location, and a cross-country route type which resulted in a straight line route that was through tree lines and other impenetrable obstacles for at least a portion of the route. The reason for establishing a planned route that did not consider available elevation and feature data was two-fold. Firstly, it is realistic to expect that map data available to maneuver forces could contain errors due to limitations of resolution and inaccurate/missing features. The second reason to prescribe such a route was to challenge the XUV to use its autonomous mobility capabilities and the multi-level path planning technologies to execute a suitable path to the goal.

Upon receiving the route plan and the command to execute, the XUV proceeded to maneuver towards the goal. During the runs, the XUV sent status update messages to the OCU that indicated to the operator the current command being executed, error messages, and system diagnostic data (e.g., fuel level). A complete log file of this information was captured and saved for each run performed. In the event that the XUV encountered an obstacle in its path, the procedure was for the XUV to autonomously attempt to maneuver around the obstacle. In order to facilitate finding a suitable path around obstacles, the assessment protocol required the XUV to follow the previously-described backup procedure in an attempt to gain a better perspective for the perception sensors. If the XUV found a suitable path around an obstacle, the system would autonomously execute that path. If, after three attempts to backup, the XUV was unable to find a path, then an operator intervention request was sent to the OCU and the previously-described intervention procedure followed.

In the event that an emergency stop was declared due to a potential for unsafe operations, the end of the run was declared. In some instances, for the sake of completeness and/or troubleshooting, the XUV was teleoperated past the trouble spot and the run resumed.

Data collected included a log of OCU entries, an ACC log, the mission plan, and a screenshot from the end of the run. Observations on the behavior of the XUV and the interaction of the Operator were manually collected by the data recorder. Dependent measures for each run included: number of backups, number of times maximum backups were reached, number of E-stops for each type (administrative E-stop or safety E-stop), number of required teleoperations, and in the case where BIP and/or FCI were included, an indication of whether or not the planning technology helped the XUV to proceed.

3. DATA INTERPRETATION

The assessment conducted in Area B9C revealed several interesting things about the interplay of the perceptive and deliberative planners and the autonomous mobility of the XUV. Table 1 shows the run schedule that was used for this area over two days in the field. Data was obtained for eleven accepted runs plus four re-execute runs.

Table 1. Run Schedule for Area B9C

Run	Planner	Global Map	BIP	FCI	A	B
1	off	off	off	off	A1	B1
2	off	off	off	off	A1	B1
3	off	on	on	off	A1	B1
4	off	on	on	off	A1	B1
5	off	on	on	on	A1	B1
6	off	off	off	off	A1	B1
7	off	off	off	off	A1	B1
8	off	on	on	off	A1	B1
9	off	on	on	off	A1	B1
10	off	on	on	on	A1	B1
11	off	on	on	on	A1	B1

The main challenge in Area B9C was the relatively narrow corridors resulting from the close layout of the shipping containers, which constrained XUV mobility requiring numerous backups in attempt to find a path. During the successive backups over the same path, the height map in the perceptive layer exhibited an artificial growth of obstacles on the ground plane which reached the minimum obstacle height and thus influenced the XUV to circumnavigate obstacles. The tight roadway also prevented the XUV from being able to turn around in the cul-de-sac and execute a new path. On one run it was shown that when the XUV was able to turn around, the new path based on updated map data enabled the XUV to achieve the goal autonomously. Another interesting situation that occurred in the cul-de-sac involved FCI. When the XUV generated a new path which ran back within the XUV sensor range, down the next side corridor (see Figure 3) and around to the goal, the lowest cost action for the XUV to continue was to go forward (through the obstacle to the yellow dot) in order to proceed along the new path. Cost is measured in meters to go around an obstacle. The XUV attempted to move forward based on the deliberative plan but could not succeed because the perceptive level planning detected the obstacle and would not proceed. The resultant behavior was the XUV moving forward, backing up when no path through the obstacle could be found, and repeating this behavior until maximum backups was reached. Table B.2 contains summary data from all runs performed in Area B9C.

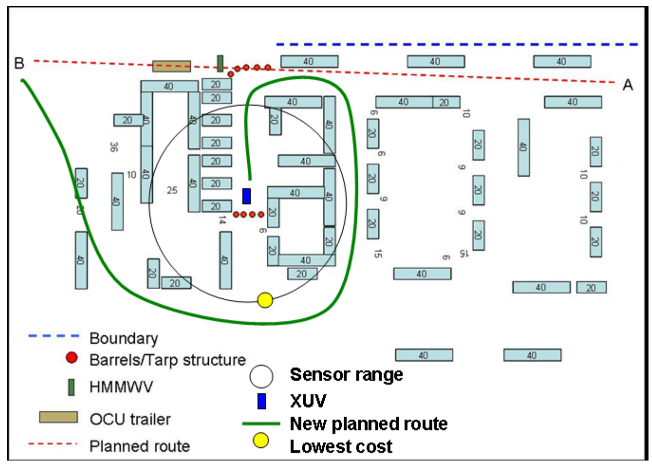

Fig. 3. Depiction of scenario with FCI and perceptive level planning power struggle

The technology assessment conducted in the portion of Area B12 yielded seven accepted runs and one re-executed run over 1.5 days in the field. The runs schedule for Area B12 is provided in Table 2.

The need for planning technologies that enable the XUV to avoid, or extricate itself from, obstructed pathways was exemplified during this portion of the technology assessment. During the runs where only the perceptive layer was used (e.g., Run1), the XUV, when faced with an obstructed path, would continually perform a figure eight pattern in search of a path through the obstacle. However, when BIP was enabled (e.g. Run 3) and given sufficient room to maneuver, the XUV demonstrated that when faced with an obstructed route it had the ability to apply BIP to plan and execute an alternative route. The behavior that was observed in area B9C wherein the perceptive layer detected obstacles and the XUV stopped but the deliberative layer planned through those same obstacles was also seen during the assessment in Area B12.

Table 2. Run Schedule for Area B12

Block	Run	Planner	Global Map	BIP	FCI	Threat	A	B
1	1	off	null	on	off	none	A1	B1
1	2	off	on	on	on	none	A1	B1
1	3	on	on	on	off	none	A1	B1
1	4	on	on	off	on	none	A1	B1
1	5	on	on	on	on	none	A1	B1
1	6	off	off	off	off	none	A1	B1
1	7	on	on	off	off	none	A1	B1
1	8	off	on	off	on	none	A1	B1
2	9	on	on	off	off	none	A2	B1
2	10	off	on	off	on	none	A2	B1
2	11	off	off	off	off	none	A2	B1
2	12	on	on	off	on	none	A2	B1
2	13	off	on	on	on	none	A2	B1
2	14	on	on	on	off	none	A2	B1
2	15	off	null	on	off	none	A2	B1
2	16	on	on	on	on	none	A2	B1
3	17	on	on	off	on	none	A1	B2
3	18	on	on	on	on	none	A1	B2
3	19	off	on	on	on	none	A1	B2
3	20	off	on	off	on	none	A1	B2
3	21	off	null	on	off	none	A1	B2
3	22	on	on	on	off	none	A1	B2
3	23	off	off	off	off	none	A1	B2
3	24	on	on	off	off	none	A1	B2

It was apparent during more than one run that the priority given to either the perceptive layer or the deliberative layer to drive mobility has a significant influence on the ability of the XUV to maneuver in the presence of obstructed pathways. Technical difficulties with the FCI demonstrated the need for further refinement to increase the robustness of that technology.

4. OBSERVATIONS

The scenarios posed to the XUV during the technology assessment enabled the research team to discover and confirm abilities and deficiencies of the path planning technologies. In addition, there were numerous technical difficulties that arose during the time in the field that the technical staff will have opportunity to address prior to the next assessment.

The interplay between the perceptive and deliberative planners was shown to have a significant impact on the behavior of the XUV when attempting to maneuver in the presence of obstructed pathways. The challenge is that if the perceptive layer is too conservative in the way that it identifies obstacles, path planning of the XUV will likely result in avoiding pathways that the XUV could traverse; however, if the deliberative layer has the final say in the executed route, the XUV is likely to enter into terrain that could potentially damage the vehicle. More work is required in developing the ability of the XUV to seamlessly use sensed and a priori data to efficiently maneuver in this type of terrain.

Best Information Planning provided a path that would enable an exit to man-made and natural cul-de-sacs that otherwise the XUV could not have overcome. It was shown that when mobility was confined such that the XUV could not turn around in the cul-de-sac, it was unable to execute a new path.

The FCI provided freedom to the XUV to search for suitable paths to the goal as designed. However, more effort is required to determine a reasonable set of scenarios and a corresponding data set that will provide insight as to the effectiveness of this technology to enable the XUV to avoid obstructed pathways. The LADAR has a maximum range of sixty meters and the surrounding terrain frequently obstructs the XUV line of sight. This limitation prevents FCI from planning around obstacles beyond the LADAR sensor range. This is important since the ACC portion of FCI plans from sixty meters out to the next way point. With a longer range sensor, FCI (with BIP) should be able to foresee cul-de-sac conditions and as a result, avoid entering them.

The handoff between the perceptive and deliberative planning layers requires further attention. A method is required to ensure that available terrain feature information is used appropriately by both layers so that the vehicle a) does not avoid a path that affords safe mobility and b) can effectively identify when a path is blocked or is too narrow that mobility becomes inherently unsafe.

It is recommended that planning based on sensed information be automated for the next assessment by removing the step that requires the operator to initiate a replan. The implications of this automation for the operator will need to be explored in future assessments. Also, it is recommended that the XUV actively perform a more complete scan of the environment, as it traverses terrain, in order to improve the quality of any new deliberative plan that is based on sensed information.

The robustness of this technology to perform as designed during field experimentation must improve in order to assess its influence on vehicle behavior. It is further recommended that simulation be leveraged to better understand the numerous parameters that influence the performance of the FCI.

In order to assess the ability of an unmanned ground vehicle to maneuver in a tactical manner through relevant terrain, a set of criteria is required to measure performance. Although summary data can be used to draw some limited qualitative conclusions, a means to quantitatively measure the ability of the vehicle to behave in a way that would benefit the Soldier is needed.

5. CONCLUSION

During 4-14 February 2008, the Army Research Laboratory and General Dynamics Robotics Systems conducted an assessment of technologies designed to enable tactical unmanned ground vehicle behaviors. The assessment provided data taken in a relevant environment that demonstrated the impact of advances in deliberative layer planning technologies to enhance autonomous mobility in a relevant environment.

As a result of this technology assessment, it was shown that the interplay between the perceptive and deliberative planning layers played an important role in vehicle path planning but requires further development. More refinement is required in order for the XUV to seamlessly use sensed and a priori data to efficiently maneuver in relevant terrain.

Recommendations for the methodology and functionality of select technologies were provided to facilitate enhancement of future field activities. The information and experience provided to the software developers and the designers as a result of the 2008 technology assessment will be applied to focus research in vehicle path planning, improve the functionality of technology components, and improve the quality of future technology assessments.

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